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J/Ψ Production in pp Collisions at $\sqrt{s} = 200$ GeV at RHIC

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We study J/ψ production in pp collisions at RHIC at $\sqrt{s}$=200 GeV within the PHENIX detector acceptance range by using color singlet and color octet model within pQCD and NRQCD. It is shown that color octet model exactly reproduce the RHIC data on p_T distribution, rapidity distribution and total cross section of J/ψ production without any absolute normalization in pp collisions at $\sqrt{s} = 200$ GeV. The color singlet model completely fails to explain the data. As color octet model works well at other collider energy such as Tevatron etc, we suggest in view of our calculation here that one can use color octet model for J/ψ production at RHIC energy. This is important because the correct mechanism for J/ψ production in pp collisions at RHIC is necessary if we want to study J/ψ suppression as a signature of quark-gluon plasma detection in AuAu collisons at $\sqrt{s} = 200$ GeV and to extract polarized gluon distribution function in polarized pp collisions at RHIC.

Understanding the J/ψ production mechanism in high energy hadronic collisions is an important topic in QCD and in collider physics. Two prominent mechanisms for J/ψ production at high energy colliders are 1)the color singlet model [1] and 2)the color octet model [2], both of which rely on pQCD and NRQCD. At Tevatron energies, the color singlet model was found to give too small a yield and the color octet mechanism for J/ψ production was then introduced [3]. It was shown that the color octet mechanism, with both parton fusion and parton fragmentation processes included, reproduced the Tevatron data [5]. The relativisitic heavy ion collider (RHIC) at Brookhaven is a unique facility which can collide unpolarized and polarized protons at $\sqrt{s}$ =200 and 500 GeV as well as two heavy nuclei such as gold on gold. It has also the capability of exploring light-heavy interactions such as the collisions pAu and dAu at $\sqrt{s} = 200$ GeV. The unpolarized pp collision data serve as a baseline for understanding collective phenomena such as the production of a quark gluon plasma that is expected in the heavy ion collisions [6] as well as providing the necessary information needed to extract interference terms generated when considering polarized pp collisions. One of the key things to be measured in Au Au collisions as well as in polarized pp collision is J/ψ production. In relativistic heavy ion collisions, J/ψ suppression has been posited to be one of the major signatures of the production of the quark-gluon plasma. In case of polarized pp collisions the measurement of J/ψ production is an important ingredient in extracting the polarized gluon distribution function for the proton directly. For that reason, understanding the dominant mechanism of J/ψ production is important. Thus it is crucial to first determine the relative importance of color singlet and color octet contributions in the existing unpolarized proton-proton scattering data at RHIC energies. In this paper we will study J/ψ production in pp

collisions at RHIC by using the color singlet and color octet models within pQCD and NRQCD. We will study the p_T distribution, rapidity distribution and total cross section of the J/ψ production at $\sqrt{s} = 200$ GeV pp collisions and compare those with the recent measurements by the PHENIX collaboration at RHIC [7].

In the color singlet model, quarkonium is formed as a non relativistic bound state of a heavy quark-antiquark pair via static gluon exchange. In this model it is assumed that the $Q\bar{Q}$ pair is produced in the color singlet state at the production point with appropriate spin (S) and orbital angular momentum quantum number (L) and then evolves into a bound state $^{2S+1}L_J$ with total angular momentum quantum number (J). The relative momentum of the $Q\bar{Q}$ pair inside the quarkonium is assumed to be small compared to the mass m of the heavy quark so that the Q and $\bar{Q}$ will not fly apart to form heavy mesons. The non-relativistic non-perturbative wave functions and its derivatives appearing in the color singlet model calculation are either determined from the potential model or taken from experiment.

The leading term in the p_T distribution for the cross section for J/ψ production first occurs at order α_s^3, since the lower order graphs lead to charmonium states with zero transverse momentum.

The p_T distribution for heavy quarkonium production in the color singlet model is given by:

$$\frac{d\sigma}{dp_T}(AB \to J/\psi, \chi_J + X) = \sum_{a,b} \int dy \int dx_a \, x_a$$

$$f_{a/A}(x_a, Q^2) \, x_b' f_{b/B}(x_b', Q^2) \, \frac{2p_T}{x_i - \frac{M_T}{\sqrt{s}}e^y}$$

$$\frac{d\hat{\sigma}}{d\hat{t}}(ab \to (^{2S+1}L_J)c) , \qquad (1)$$

where

$$x'_b = \frac{1}{\sqrt{s}} \frac{x_b\sqrt{s}M_T e^{-y} - M^2}{x_b\sqrt{s} - M_T e^y}. \tag{2}$$

In the above equation a, b, c are light quarks and gluons. $f(x, Q^2)$ is the parton distribution function at longitudinal momentum fraction x and at factorization scale Q. M is the mass of the bound state quarkonium and $M_T = \sqrt{p_T^2 + M^2}$. The partonic level differential cross section $\frac{d\hat{\sigma}}{d\hat{t}}(ab \to (^{2S+1}L_J)c)$ contain the non-relativistic wave function $|R(0)|^2$ (for direct J/ψ process) and its derivatives $|R'(0)|^2$ (for χ_J processes) at the origin [1]. For the non relativistic wave functions at the origin we take the Buchmuller-Tye wave function [8]. The numerical value is [8]: $|R(0)|^2$=0.81 GeV^3. For the derivative of the radial wave function at origin we use [9] $\frac{9}{2\pi} \frac{|R'(0)|^2}{M_c^4}$=15 MeV.

In the color octet model relativistic effects are taken into account which are neglected in the color singlet model. In the color octet model using an effective field theory called non-relativistic QCD (NRQCD), the dynamical gluon enters into Fock state decompositions of the quarkonium states. In NRQCD the expansion is carried out in terms of the relative velocity v ($v^2 \sim 0.23$ for $C\bar{C}$ system and 0.1 for $B\bar{B}$ system) of the $Q\bar{Q}$ bound state. The NRQCD Lagrangian density is given by

$$\mathcal{L}_{NRQCD} = \mathcal{L}_{light} + \mathcal{L}_{heavy} + \mathcal{L}_{correction} \tag{3}$$

In the above equation light refers to light quarks and gluons, heavy refers to lowest order non-relativistic heavy quarks part and correction is higher order corrections in heavy quark sector. The explicit expressions for the three terms can be found in [3] In NRQCD the dynamical gluons enter into the Fock state decompositions of different physical states. The wave function of an S-wave orthoquarkonia state $|\psi_Q >$ is expanded as follows:

$$|\psi_Q > = O(1)|Q\bar{Q}[^3S_1^{(1)}] > + O(v)|Q\bar{Q}[^3P_J^{(8)}]g >$$
$$+ O(v^2)|Q\bar{Q}[^3S_1^{(1,8)}]gg > + O(v^2)|Q\bar{Q}[^1S_0^{(8)}]g >$$
$$+ O(v^2)|Q\bar{Q}[^3D_J^{(1,8)}]gg > + ... \tag{4}$$

and the wave functions of a P-wave orthoquarkonium state $|\chi_{QJ} >$ has a similar expansion:

$$|\chi_{QJ} >= O(1)|Q\bar{Q}[^3P_J^{(1)}] > + O(v)|Q\bar{Q}[^3S_1^{(8)}]g >$$
$$+ O(v^2).... \tag{5}$$

In the above equation (1,8) refers to singlet and octet state of the $Q\bar{Q}$ pair. After a $Q\bar{Q}$ is formed in its color octet state it may absorb a soft gluon and transform into $|\chi_{QJ} >$ via eq. (5) and then become a J/ψ by photon decay. The $Q\bar{Q}$ pair in the color octet state can also emit two long wavelength gluons and become a J/ψ via eq. (4) and so on. The non-perturbative matrix elements can be fitted from other experiments or can be determined from lattice calculations.

In the color octet model the p_T distribution differential cross section for J/ψ production is given by:

$$\frac{d\sigma}{dp_T}(AB \to \psi_Q(\chi_J) + X) = \sum_{a,b} \int dy \int dx_a \, x_a$$
$$f_{a/A}(x_a, Q^2) \, x'_b f_{b/B}(x'_b, Q^2) \times \frac{2p_T}{x_a - \frac{M_T}{\sqrt{s}}e^y}$$
$$\frac{d\hat{\sigma}}{d\hat{t}}(ab \to C\bar{C}[^{2S+1}L_J^{(8)}]c \to \psi_Q(\chi_J)) \tag{6}$$

The partonic level differential cross section is given by

$$\frac{d\hat{\sigma}}{d\hat{t}}(ab \to C\bar{C}[^{2S+1}L_J^{(8)}]c \to \psi_Q(\chi_J)) = \frac{1}{16\pi\hat{s}^2}$$
$$\Sigma |\mathcal{A}(ab \to C\bar{C}[^{2S+1}L_J^{(8)}]c)_{short}|^2 < 0|\mathcal{O}_8^{\psi_Q(\chi_J)}(^{2S+1}L_J)|0 > \tag{7}$$

The partonic level matrix elements squared

$$\Sigma |\mathcal{A}(ab \to C\bar{C}[^{2S+1}L_J^{(8)}]c)_{short}|^2$$

and the non-perturbative matrix elements

$$< 0|\mathcal{O}_8^{\psi_Q(\chi_J)}(^{2S+1}L_J)|0 >$$

are taken from [10].

For the rapidity distribution and total cross section of J/ψ production the leading contribution is proportional to α_s^2 and we will only consider that contribution here. For the J/ψ to have non-vanishing transverse momentum, one has to include order α_s^3 terms which we considered earlier. In leading order, the parton fusion processes contribute to the total cross section for J/ψ (χ_J) production in pp collisions as follows:

$$\sigma^{pp \to J/\psi(\chi_J)} = \Sigma_{a,b} \int dx_a \int dx_b f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2)$$
$$\sigma^{ab \to J/\psi(\chi_J)}(\hat{s})\delta(x_a x_b - 4m^2/s) \tag{8}$$

where $\sigma^{ab \to J/\psi(\chi_J)}(\hat{s})$ is the partonic level cross section at leading order. In the above equation m is the mass of the charm quark. At the leading order not all the processes contribute to the total cross section in the singlet and octet channel due to various quantum number conservation laws. In the color singlet channel the J/ψ production cross section is given by:

$$\sigma_1^{pp \to J/\psi}(s) = \sigma_1^{pp \to \chi_0}(s)BR_{\chi_0}, + \sigma_1^{pp \to \chi_2}(s)BR_{\chi_2}, \tag{9}$$

Here BR_χ refers to the branching ratio of a χ to decay into a J/ψ. Similarly in the octet channel at the leading order the J/ψ production cross section is given by:

$$\sigma_8^{pp \to J/\psi}(s) = \sigma_8^{pp \to J/\psi}(s) + \sigma_8^{pp \to \chi_1}(s)BR_{\chi_1}$$
$$+ \sigma_8^{pp \to \chi_0}(s)BR_{\chi_0} + \sigma_8^{pp \to \chi_2}(s)BR_{\chi_2}, \tag{10}$$

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In the above equations the direct J/ψ production and the decay of χ_c with their correcsponding branching ratios to J/ψ in both singlet and octet channels are included.

The rapidity distribution for J/ψ production is given by

$$\frac{d\sigma}{dy} = \Sigma_{a,b} x_a \int dx_b f_{a/d}(x_a, Q^2) f_{b/A}(x_b, Q^2)$$
$$\sigma^{ab \to J/\psi}(\hat{s}) \delta(x_a x_b - 4m^2/s) \qquad (11)$$

where the rapidity y is related to x_a by

$$x_a = \frac{2m}{\sqrt{s}} e^y. \qquad (12)$$

In the leading order we use the same values of the non-perturbative matrix elements used in the singlet and octet channels as in [11].

We will use the GRV98 [12] and MRST [13] parton distribution functions inside the proton. The factorization scales are set to be $Q = 2m$ for the total cross section and rapidity distribution plots, and $Q = \sqrt{p_T^2 + M^2}$ for the plot of the p_T distribution.

In Fig.1 we present the p_T distribution of the J/ψ production cross section separately for the color singlet and color octet model including the effects of cuts due to the PHENIX detector acceptance range. We have considered all the parton fusion processes [10,6] in our calculation. The upper line is the color octet result and the lower line is the color singlet result. In this plot we have used the GRV98 parton distribution functions. We have compared our calculation with the recent PHENIX data (run3). The daggers are recent PHENIX data taken from [7]. It can be seen from the figure that the color singlet model contriubtion is more than an order of magnitude smaller than the octet model contribution. On the other hand color octet model with only parton fusion processes reproduces the recent PHENIX data very well. Thus for $p_T \leq 5 GeV$ we do not need contributions from the parton fragmentation processes. We have not compared our calculation with the data below p_T equals to 2 GeV as pQCD calculations are not valid at such low transverse momenta. In the near future PHENIX will take data up to $p_T = 10 GeV$. This new data will allow us to decide whether fragmentation processes contributions within color octet model are important at higher p_T and whether their inclusion will allow us to understand the data.

In Fig. 2 we present the rapidity distribution of the J/ψ production cross section in pp collisions at RHIC at $\sqrt{s} = 200$ GeV. We have taken the charm quark mass equal to 1.45 GeV in our calculation. The solid line is obtained by using GEV98 PDF's and dashed line is obtaine by using MRST99 PDF's. The PHENIX experimental data are shown in the figure as daggers. The rapidity range covered by PHENIX at RHIC is from $-3 < y < 3$. The color singlet contribution is also shown as dot-dashed

line (here we only show the results using the GRV98 PDF's) which is very small when compared with the color octet contribution. It can be seen that just including the color octet contribution explains the run3 PHENIX data.

Finally, we present the total cross section for J/ψ production in pp collisions at $\sqrt{s} = 200$ GeV at RHIC and conpare it with the run3 PHENIX data. In the color octet model we find $B\sigma_{J/\psi} = 159$ (nb) which is in very good agreement with the PHENIX collaoration experimental value which is reported as 159 (nb). In the above total cross section computation we have used charm quark mass equal to 1.45 GeV and the MRST99 parton distribution function inside the proton in our calculation. The agreement of color octet model predictions with the PHENIX experimental data is remarkable in all aspects, $i.e.$ in p_T distribution, in rapidity distribution and in total cross section measurements at $\sqrt{s} = 200$ GeV pp collisions.

In summary, in this letter, we have studied J/ψ production in pp collisions at RHIC at $\sqrt{s} = 200$ GeV within the PHENIX detector acceptance range by using the color singlet and the color octet model within pQCD and NRQCD and have compared them with the recent PHENIX experimental data. We have demonstrated that the color octet model using only parton fusion processes is able to reproduce the RHIC data on the p_T distribution, rapidity distribution and total cross section of J/ψ production. This is done without any normalization factor modifications and using matrix elements extracted from the Tevatron and other experiments. The color singlet model gives negligible contributions when compared to the octet contributions at this energy. Our results confirm the applicability of the color octet model found at the Tevatron.

It is important to identify the correct mechanism for J/ψ production in pp collisions at RHIC if we want to study J/ψ suppression as a signature of quark-gluon plasma detection in AuAu collisons at $\sqrt{s} = 200$ GeV [14]. It is also important if we hope to extract the polarized gluon distribution function from the data on polarized pp collisions at RHIC. The latter will be important for isolating interference terms which can be used to explore various models which predict non standard model TeV physics.

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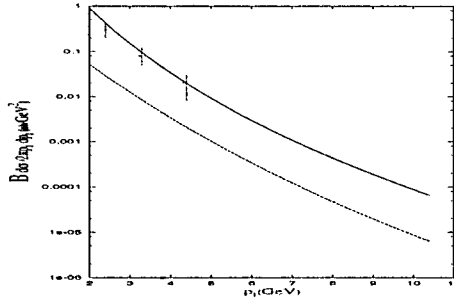
FIG. 1: p_T distribution of J/ψ production cross section in pp collisions at $\sqrt{s} = 200$ GeV at RHIC in the PHENIX detector acceptance range. The upper(lower) line is color octet(singlet) model predictions. The cross spots are run3 PHENIX experimental data. B is branching ratio of J/ψ to leptons.
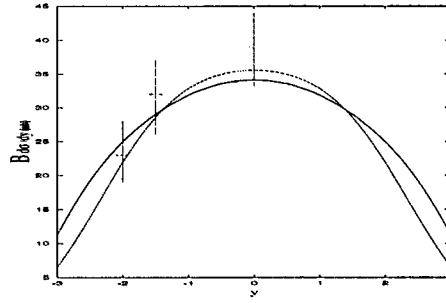

FIG. 2: Rapidity distribution of J/ψ production cross section in pp collisions at $\sqrt{s} = 200$ GeV at RHIC in the PHENIX detector acceptance range. The solid(dashed) line is color octet model predictions with GRV98(MRST99) PDF's. The dot dashed line is color singlet model predictions using GRV98 PDF's. The cross spots are run3 PHENIX experimental data. B is branching ratio of J/ψ to leptons.

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